

## Plasma Arc Torch and Method for Improved Life of Plasma Arc Torch Consumable Parts

### Background of the Invention

The present invention relates generally to plasma arc torches and, in particular, to consumable parts utilized in plasma arc torches and methods for improving the useful life of such consumable parts.

Plasma arc torches, also known as electric arc torches, are commonly used for cutting and welding metal workpieces by directing a plasma consisting of ionized gas particles toward the workpiece. In a typical plasma torch, a gas to be ionized is supplied to a lower end of the torch and flows past an electrode before exiting through an orifice in the torch tip. The electrode, which is a consumable part, has a relatively negative potential and operates as a cathode. The torch tip (nozzle) surrounds the electrode at the lower end of the torch in spaced relationship with the electrode and constitutes a relatively positive potential anode. The gas to be ionized typically flows through the chamber formed by the gap between the electrode and the tip in a generally swirling or spiraling flow pattern. When a sufficiently high voltage is applied to the electrode, an arc is caused to jump the gap between the electrode and the torch tip, thereby heating the gas and causing it to ionize. The ionized gas in the gap is blown out of the torch and appears as an arc that extends externally off the tip. As the head or lower end of the torch is moved to a position close to the workpiece, the arc jumps or transfers from the torch tip to the workpiece because the impedance of the workpiece to ground is made lower than the impedance of the torch tip to ground. During this "transferred arc" operation, the workpiece itself serves as the anode. A shield cap is typically secured on the torch body over the torch tip and electrode to complete assembly of the torch.

In addition to the electrode, other parts of the plasma arc torch are typically consumed during repeated operation of the torch, including the torch tip and the shield cap surrounding the tip. These consumable parts are consumed as a result of the destructive effects of the high heat environment, and effective management of the heat generated in and on these parts is critical to improving the useful life of the consumable parts. For example, heat is generated in the body of the electrode primarily by interaction with the heated plasma at its front face. Additional heat is generated in the electrode body by ohmic heating resulting from current flow. All of this heat in the electrode must be dissipated by conduction through the electrode body to a cooling mechanism.

To this end, it is known to provide a fluid cooled plasma arc torch in which the electrode is cooled primarily by high velocity plasma gas swirling through a plasma chamber formed by a gap between the electrode and surrounding tip. Plasma gas is directed over the outer surface of the electrode before it is ionized and exits through the tip orifice. A similar condition exists for the torch tip and the shield cap of a plasma arc torch. Heat developed in the tip and the shield cap is dissipated by convection to plasma gas flowing on the inside of the tip and by convection to secondary gas flowing on the outside of the tip. It is well established that cooling of the tip and the electrode during operation of the torch improves the useful life of these components.

Convective heat transfer (i.e., cooling) as discussed herein is the mechanism of heat removal in which heat in a body is deposited into fluid flowing over the surface of the body. The effectiveness of the cooling fluid flowing over the surface is referred to as the convective heat transfer coefficient  $h$ , which is impacted by velocity of the fluid flow, turbulence of the fluid flow, physical properties of the fluid, and interactions with surface geometry. In any convective cooling approach, a consequence of the fluid–surface interaction is the development of a region in the fluid adjacent to the surface, through which the fluid flow velocity varies from zero at the surface to a finite value associated with the bulk fluid flow

near the center of the flow passage. This region is known as the hydrodynamic boundary layer. As illustrated in FIG. 13, in fully developed turbulent flow this boundary layer consists of three sublayers: a laminar sublayer adjacent the surface, an intermediate buffer layer and a turbulent outer layer. Heat transport across the laminar sublayer is dominated by conduction, while heat transport in the intermediate and turbulent layers is substantially augmented by the convective motion of the eddies present in these layers. The overall effect is that heat transfer from the surface to be cooled is substantially increased by the presence of turbulence in the boundary layer. Effective means for increasing convective heat transfer thus rely on increasing turbulence and mixing in the boundary layer, either by increasing the flow velocity or by promoting mixing or turbulence in the boundary layer as illustrated in Fig. 14.

### **Summary of the Invention**

Among the several objects and features of the present invention is the provision of a plasma arc torch which enhances convective cooling of the consumable parts of the torch; the provision of such a torch in which the useful life of the consumable parts is increased; and the provision of such a torch in which the electrode is capable of a threadless quick connect/disconnect connection with the cathode of the torch.

Among additional objects and features of the present invention is the provision of a method which increases the useful life of the consumable parts of a plasma arc torch; and the provision of such a method which enhances convective cooling of the consumable parts of the torch.

Other objects and features will be in part apparent and in part pointed out hereinafter.

In general, a plasma arc torch of the present invention comprises a cathode and an electrode electrically connected to the cathode. A tip surrounds at least a portion of the electrode in spaced relationship therewith to define a gas passage. The gas passage is in fluid

communication with a source of working gas for receiving working gas into the gas passage such that working gas within the gas passage swirls about the outer surface of the electrode. The tip has a central exit orifice in fluid communication with the gas passage. The outer surface of the electrode is textured to promote turbulence of working gas flowing over the outer surface of the electrode as working gas swirls within the gas passage for enhancing convective cooling of the electrode.

In another embodiment, a plasma arc torch of the present invention comprises a cathode and an electrode electrically connected to the cathode. A tip surrounds a portion of the electrode in spaced relationship therewith to define a primary gas passage. The primary gas passage is in fluid communication with a source of primary working gas for receiving primary working gas into the gas passage such that the primary working gas flows over an inner surface of the tip in the gas passage. The tip has a central exit orifice in fluid communication with the gas passage. The inner surface of the tip is textured to promote turbulence of the working gas flowing through the gas passage over the inner surface of the tip for enhancing convective cooling of the tip.

In yet another embodiment, a plasma arc torch of the present invention comprises a cathode and an electrode electrically connected to the cathode. A tip surrounds a portion of the electrode in spaced relationship therewith to define a primary gas passage. The primary gas passage is in fluid communication with a source of primary working gas for receiving primary working gas into the gas passage. The tip has a central exit orifice in fluid communication with the gas passage. A shield cap surrounds the tip in spaced relationship with an outer surface of the tip to define a secondary gas passage for directing gas through the torch over the outer surface of the tip. The shield cap has at least one opening therein for exhausting gas in the secondary gas passage from the torch. The outer surface of the tip is textured to promote turbulence of the gas flowing through the secondary gas passage over the outer surface of the tip for enhancing convective cooling of the tip.

Another plasma arc torch of the present invention generally comprises a cathode and an electrode electrically connected to the cathode. A tip surrounds a portion of the electrode in spaced relationship therewith to define a primary gas passage. The primary gas passage is in fluid communication with a source of primary working gas for receiving primary working gas into the gas passage. The tip has a central exit orifice in fluid communication with the gas passage. A shield cap surrounds the tip in spaced relationship therewith to define a secondary gas passage for directing gas through the torch over an inner surface of the shield cap. The shield cap has at least one opening therein for exhausting gas in the secondary gas passage from the torch. The inner surface of the shield cap is textured to promote turbulence of the gas flowing through the secondary gas passage over the inner surface of the shield cap for enhancing convective cooling of the shield cap.

In general, an electrode of the present invention for use in a plasma arc torch of the type having a cathode, a gas passage defined at least in part by the electrode and a tip surrounding the electrode in spaced relationship therewith and working gas flowing through the gas passage in a generally swirling direction about an outer surface of the electrode generally comprises an upper end adapted for electrical connection to the cathode. A lower end face of the electrode has a recess therein. An insert constructed of an emissive material is disposed in the recess of the lower end face. A longitudinal portion of the electrode intermediate the upper end and the lower end face of the electrode defines at least in part the gas passage through which working gas flows in a generally swirling direction about the electrode. The outer surface of the longitudinal portion of the electrode is textured to promote turbulence of the working gas swirling within the gas passage over the outer surface of the longitudinal portion of the electrode.

A torch tip of the present invention for use in a plasma arc torch of the type having a cathode, a primary gas passage defined at least in part by an electrode electrically connected to the cathode and the tip surrounding the electrode in spaced relationship therewith and

working gas flowing through the primary gas passage generally comprises a lower end having a central exit orifice in fluid communication with the primary gas passage for exhausting working gas from the primary gas passage. An inner surface of the torch tip is exposed for fluid contact by working gas in the primary gas passage. The inner surface of the tip is textured to promote turbulence of the gas flowing through the primary gas passage over the inner surface of the tip for enhancing convective cooling of the tip.

In another embodiment, a torch tip of the present invention for use in a plasma torch similar to that above and further having a shield cap surrounding at least a portion of the tip in spaced relationship therewith to define a secondary gas passage through which working gas flows generally comprises a lower end having a central exit orifice in fluid communication with the primary gas passage for exhausting working gas from the primary gas passage. An outer surface of the torch tip is exposed for fluid contact by working gas in the secondary gas passage. The outer surface of the tip is textured to promote turbulence of the gas flowing through the secondary gas passage over the outer surface of the tip for enhancing convective cooling of the tip.

A shield cap of the present invention for use in a plasma arc torch of the type having a cathode, a primary gas passage defined at least in part by an electrode electrically connected to the cathode and a tip surrounding the electrode in spaced relationship therewith and working gas flowing through the primary gas passage, with the shield cap surrounding at least a portion of the tip in spaced relationship therewith to define a secondary gas passage through which working gas flows, generally comprises a lower end having at least one exhaust orifice in fluid communication with the secondary gas passage for exhausting working gas from the secondary gas passage. An inner surface of the shield cap is exposed for fluid contact by working gas in the secondary gas passage. The inner surface of the shield cap is textured to promote turbulence of the gas flowing through the secondary gas passage over the inner surface of the shield cap for enhancing convective cooling of the shield cap.

A series of electrodes of the present invention generally comprises at least two interchangeable electrodes, with each electrode corresponding to a different current level at which the torch is operable. The outer surface of each electrode is textured to promote turbulence of the working gas flowing over the outer surface of the electrode as working gas swirls about the electrode in the gas passage. The cross-sectional area of the textured outer surface of each electrode increases as the current level at which the torch can be operated decreases to thereby decrease the cross-sectional area of the gas passage as the current level decreases.

A series of torch tips of the present invention generally comprises at least two interchangeable tips, with each tip corresponding to a different current level at which the torch is operable. The central exit orifice of the tips substantially decreases as the current level at which the torch can be operated decreases. Each tip has an inner surface defining an inner cross-sectional area of the tip. The inner cross-sectional area of the tips substantially increases as the current level at which the torch can be operated decreases.

In general, a series of electrode and tip sets of the present invention comprises a plurality of electrode and tip sets, with each set corresponding to a different current level at which the torch is operable. Each set comprises an electrode having a textured outer surface to promote turbulence of the working gas flowing over the outer surface of the electrode as the working gas swirls about the electrode, and a tip. The size of the central exit orifice of the tip decreases for each set as the current level at which the torch is operable decreases. The electrode and tip of each set are sized relative to each other such that the cross-sectional area of the gas passage defined therebetween decreases for each set as the current level at which the torch is operable decreases.

A method of the present invention for improving the useful life of an electrode used in a plasma arc torch generally comprises directing working gas through a gas passage defined by an electrode and a tip surrounding the electrode for exhaust from the torch through a

central exit orifice of the tip. The working gas swirls within the gas passage about the electrode to flow over an outer surface of the electrode as it is directed through the gas passage to define a hydrodynamic boundary layer generally adjacent the outer surface of the electrode. The boundary layer includes a turbulent outer layer. Gas is turbulated in the hydrodynamic boundary layer generally adjacent the outer surface of the electrode as gas is directed through the gas passage to increase turbulent flow in the boundary layer for enhancing convective cooling of the electrode thereby to improve the useful life of the electrode.

A method of the present invention for improving the useful life of a torch tip generally comprises directing working gas through a secondary gas passage of the torch for exhaust from the torch through at least one opening of the shield cap. The working gas flows over an outer surface of the torch tip as it is directed through the secondary gas passage to define a hydrodynamic boundary layer adjacent the outer surface of the torch tip. The boundary layer includes a turbulent outer layer. Gas is turbulated in the hydrodynamic boundary layer adjacent the outer surface of the torch tip as gas is directed through the secondary gas passage to increase turbulent flow in the boundary layer for enhancing convective cooling of the torch tip thereby to improve the useful life of the torch tip.

A method of the present invention for improving the useful life of a shield cap generally comprises directing working gas through a secondary gas passage of the torch for exhaust from the torch through the least one opening of the shield cap. The working gas flows over an inner surface of the shield cap as it is directed through the secondary gas passage to define a hydrodynamic boundary layer adjacent the inner surface of the shield cap. The boundary layer includes a turbulent outer layer. Gas is turbulated in the hydrodynamic boundary layer adjacent the inner surface of the shield cap as gas is directed through the secondary gas passage to increase turbulent flow in the boundary layer for enhancing convective cooling of the shield cap thereby to improve the useful life of the shield cap.



A method of the present invention for improving the useful life of an electrode or tip of a plasma arc torch generally comprises texturing the surface of at least one of the electrode and tip to promote turbulence of working gas flowing within the gas passage over the textured surface of said at least one of the electrode and tip. The method also includes changing the level of electrical current supplied to the electrode. One or more of the following parameters is modified in response to the change in current: (1) the standard volumetric gas flow rate through said annular gas passage, and (2) the dimensions of the annular gas passage.

### **Brief Description of the Drawings**

FIG. 1 is a vertical section of a torch head of a plasma torch with an electrode of the torch head shown in full;

FIG. 2 is an exploded vertical section of the plasma torch head of FIG. 1;

FIG. 3 is an exploded perspective of the plasma torch head of FIG. 1;

FIG. 4 is a section taken in the plane of line 4-4 of FIG. 1;

FIG. 5 is an expanded vertical section of a portion of the torch head of FIG. 1 showing respective connecting ends of the electrode and a cathode;

FIG. 6 is a vertical section of a torch head of plasma torch of a second embodiment of the present invention;

FIG. 7 is an exploded vertical section of the plasma torch head of FIG. 6;

FIG. 8 is an exploded perspective of the plasma torch head of FIG. 6;

FIG. 9 is an expanded vertical section of a portion of the torch head of FIG 6 showing respective connecting ends of the electrode and a cathode;

FIGS. 10a-c are elevations of various embodiments of the electrode of the plasma arc torch of FIG. 1, with the outer surface of the electrode textured in accordance with the present invention;

FIG. 11 is vertical section similar to FIG. 1, with an outer surface of the tip textured in accordance with the present invention;

FIG. 11a is a vertical section similar to FIG. 11, with an inner surface of the tip textured in accordance with the present invention instead of the outer surface of the tip;

FIG. 12 is a partial section of another embodiment of a torch head of a plasma arc torch of the present invention with an inner surface of a shield cap textured in accordance with the present invention;

FIG. 13 is a schematic illustration of a conventional hydrodynamic boundary layer comprising a laminar sublayer, intermediate buffer layer and outer turbulent layer;

FIG. 14 is a schematic illustration of a hydrodynamic boundary layer for flow over a textured surface such as the electrode of FIGS 10a-c; and

FIG. 15 is a table of data from an experiment illustrating the increase in useful lifetime of an electrode consumable of the present invention; and

### **Detailed Description of the Preferred Embodiments**

With reference to the various drawings, and in particular to FIG. 1, a torch head of a plasma torch of the present invention is generally indicated at 31. The torch head 31 includes a cathode, generally indicated at 33, secured in a torch body 35 of the torch at an upper end of the torch head, and an electrode, generally indicated at 37, electrically connected to the cathode. A central insulator 39 constructed of a suitable electrically insulating material, such as a polyamide or polyimide material, surrounds a substantial portion of both the cathode 33 and the electrode 37 to electrically isolate the cathode and electrode from a generally tubular anode 41 that surrounds a portion of the insulator.

The cathode 33 and electrode 37 are configured for a coaxial telescoping connection (broadly, a threadless quick connect/disconnect connection) with one another on a central longitudinal axis X of the torch. To establish this connection, the cathode 33 and electrode

37 are formed with opposing detents generally designated 43 and 45, respectively. As will be described hereinafter, these detents 43, 45 are interengageable with one another when the electrode 37 is connected to the cathode 33 to inhibit axial movement of the electrode away from the cathode.

5       The cathode 33 is generally tubular and comprises a head 51, a body 53 and a lower connecting end 55 adapted for coaxial interconnection with the electrode 37 about the longitudinal axis X of the torch. A central bore 57 extends longitudinally substantially the length of the cathode 33 to direct a working gas through the cathode. An opening 59 in the cathode head 51 is in fluid communication with a source of primary working gas (not shown) to receive working gas into the torch head 31. The bottom of the cathode 33 is open to exhaust gas from the cathode. The cathode 33 of the illustrated embodiment is constructed of brass, with the head 51, body 53 and lower connecting end 55 of the cathode preferably being of unitary construction. However, it is understood that the head 51 may be formed separate from the body 53 and subsequently attached to or otherwise fitted on the cathode body without departing from the scope of this invention.

15       Referring to FIGS. 1 and 3, the connecting end 55 of the cathode 33 comprises a set of resilient longitudinally extending prongs 61 defined by vertical slots 63 in the cathode extending up from the bottom of the cathode. The prongs 61 have upper ends 65 integrally connected to the body 53 of the cathode 33 and free lower ends 67 which are offset radially outwardly so that each prong has an upper radial shoulder 69 and a lower radial shoulder 71. The prongs 61 are sufficiently resilient to permit generally radial movement of the prongs between a normal, undeflected state (FIGS. 2 and 5) and a deflected state (FIG.1) in which the prongs are deflected outward away from each other and the central longitudinal axis X of the torch to increase the inner diameter of the cathode connecting end 55 to enable the electrode 37 to be inserted up into the cathode, as will be described. The radial outward

movement of the prongs 61 is permitted by an annular gap 73 formed between the connecting end 61 of the cathode 33 and the central insulator 39.

In the preferred embodiment, the detent 43 on the cathode 33 comprises a cap 75 of electrically insulating material fitted on the lower end 67 of each prong 61. Thus, it will be seen that the detent 43 is on the connecting end 61 of the cathode 33 for conjoint radial movement with the prongs between an undeflected and deflected state. As best illustrated in FIG. 5, the cap 75 is generally J-shaped in vertical section, comprising an outer wall 77, an inner wall 79 and a bottom wall 81 which define a recess 83 for receiving the offset lower end 67 of the prong 61. The outer wall 77 of the cap 75 and the lower end 67 of the prong 61 have a tongue and groove connection for securely holding the cap on the prong. Significantly, the thickness of the inner wall 79 below the lower radial shoulder 71 of the prong 61 is greater than the width of the lower radial shoulder of the prong so that a portion of the inner wall projects radially inwardly beyond the lower shoulder to define a generally radial detent surface 85 of the cathode detent 43. A sleeve 87 of electrically insulating material is disposed on the inside of the cathode 33 at a location spaced above the radial detent surfaces 85, leaving a portion of the inside wall of the metal cathode exposed to function as an electrical contact surface 89 for the electrode 37. An inner edge 91 of the bottom of the cathode 33 (e.g., of the insulating end caps 75) is tapered outward to provide a cam surface engageable by the electrode 37 upon insertion of the electrode into the cathode to initiate outward displacement of the prongs 61 to their deflected state. The amount of insertion force required to deflect the prongs 61 may vary, but approximately 5 lbs. of axially directed force has been found to be suitable.

The inner diameter D1 (FIG. 5) of the cathode 37 at the contact surface 89 is preferably about 0.208 inches; the inner diameter D2 of the cathode at the insulating end caps 75 is preferably about 0.188 inches; and each radial detent surface 85 preferably projects radially inward from the contact surface approximately 0.01 inches. However, it will be

understood that these dimensions may vary. Also, in the preferred embodiment the connecting end 55 of the cathode 33 comprises four resilient prongs 61, but this number may vary from one prong to many prongs without departing from the scope of this invention.

Moreover, the radial detent surfaces 85 may be formed in ways other than by the caps 75.

For example, the caps 75 may be eliminated entirely, and the detent surfaces 85 may be formed by machined radial grooves or recesses (not shown) in the prongs 61, or by otherwise forming radially inwardly projecting surfaces (not shown) on the prongs.

Referring again to FIGS. 1 and 3, the electrode 37 is generally cylindric and has a solid lower end 101, an upper connecting end 105 adapted for coaxial telescoping connection with the lower connecting end 55 of the cathode 33 about the longitudinal axis X, and a gas distributing collar 103 intermediate the upper and lower ends of the electrode. The electrode 37 of the illustrated embodiment is constructed of copper, with an insert 107 of emissive material (e.g., hafnium) secured in a recess 109 in the bottom of the electrode in a conventional manner. The gas distributing collar 103 extends radially outward relative to the upper and lower ends 105, 101 of the electrode 37, defining a shoulder 111 between the gas distributing collar and the upper connecting end of the electrode. A central bore 113 of the electrode 37 extends longitudinally within the upper connecting end 105 generally from the top of the electrode down into radial alignment with the gas distributing collar 103. It is understood that the collar 103 may be other than gas distributing, such as by being solid, whereby the gas is distributed in another manner, without departing from the scope of this invention.

The central insulator 39 includes an annular seat 115 extending radially inward to define an inner diameter of the central insulator that is substantially less than the outer diameter of the gas distributing collar 103 such that the shoulder 111 formed by the gas distributing collar engages the annular seat 115 to limit insertion of the electrode 37 in the cathode 33 and axially position the electrode in the torch head 31. The top of the electrode 37

is open to provide fluid communication between the cathode central bore 57 and the electrode central bore 113 upon coaxial interconnection of the electrode and cathode 33. Opening 117 extend radially within the gas distributing collar 103 and communicate with the central bore 113 in the electrode connecting end 105 to exhaust working gas from the electrode 37.

5 With reference to FIG. 5, the outer diameter of the electrode connecting end 105 is predominately of a diameter less than the inner diameter D2 of the connecting end 55 of the cathode 33 at the insulating end caps 75 (e.g., at the cathode detent 43). However, the detent 45 on the electrode 37 comprises an annular protrusion 119 projecting generally radially outward from the connecting end 105 of the electrode such that the outer diameter of the  
10 electrode connecting end at the detent is substantially greater than the diameter of the inner surface of the cathode, including the cathode inner diameters D2 at the cathode detent 43 and D1 at the contact surface 89 above the cathode detent. For example, the electrode connecting end 105 of the illustrated embodiment preferably has an outer diameter of about 0.182 inches; and the outer diameter of the electrode connecting end at the electrode detent 45 is preferably  
15 about 0.228 inches.

The annular protrusion 119 constituting the electrode detent 45 is preferably rounded to provide an upper cam surface 121 engageable with the tapered inner edge 91 of the bottom of the cathode 33 to facilitate insertion of the electrode connecting end 105 into the cathode connecting end 55. The rounded protrusion 119 also includes a lower radial detent surface  
20 123 engageable with the radial detent surfaces 85 of the cathode detent 43 to inhibit axial movement of the electrode connecting end 105 out of the cathode connecting end 55. It is contemplated that the electrode detent 45 may be other than annular, such as by being segmented, and may be other than rounded, such as by being squared or flanged, and remain within the scope of this invention as long as the detent has a radial detent surface engageable  
25 with the radial detent surfaces 85 of the cathode detent 43. It is also contemplated that the detent may be formed separate from the electrode and attached or otherwise connected to the

electrode, and may further be resilient, and remain within the scope of this invention. The axial position of the detent 45 on the connecting end 105 of the electrode 37 may also vary and remain within the scope of this invention, as long as the length of the electrode connecting end 105 is sufficient such that when the shoulder 111 of the gas distributing collar 103 engages the annular seat 115 of the central insulator 39, the electrode detent is disposed in the cathode 33 above the cathode detent 43 in electrical engagement with the contact surface 89 of the cathode.

As shown in FIGS. 1-3, a metal tip 131, also commonly referred to as a nozzle, is disposed in the torch head 31 surrounding a lower portion of the electrode 37 in spaced relationship therewith to define a gap forming a gas passage 133 between the tip and the electrode. The gas passage 133 is further defined by a tubular gas distributor 135 extending longitudinally between the tip 131 and the gas distributing collar 103 of the electrode 37 around the lower end of the electrode in radially spaced relationship therewith. The gas distributor 135 regulates the flow of working gas through the gas passage 133. The tip 131, electrode 37 and gas distributor 135 are secured in axially fixed position during operation of the torch by a shield cup 137 comprising an exterior housing 139 of heat insulating material, such as fiberglass, and a metal shield insert 141 secured to the interior surface of the housing. The exterior housing 139 has internal threads (not shown) for threadable engagement with corresponding external threads (not shown) on the torch body 35.

The lower end of the central insulator 39 is radially spaced from the gas distributor 135 and the electrode gas distributing collar 103 to direct gas flowing from the openings 117 in the collar into a chamber 143 defined by the central insulator, gas distributor, tip 131 and shield cup insert 141. The gas distributor 135 has at least one opening (not shown) in fluid communication with both the gas passage 133 and the chamber 143 to allow some of the gas in the chamber to flow into the gas passage and out of the torch through an exit orifice 145 in the tip for use in forming the plasma arc. In the illustrated embodiment, working gas is

directed by the gas distributor 135 to flow through the gas passage 133 in a generally swirling or spiral direction about the electrode 37 (e.g., in a generally clockwise direction from the upper end to the lower end of the gas passage) as indicated by the flow arrow in FIG. 1. The remaining gas in the chamber 143 flows through an opening 147 in the shield cap insert 141 into a secondary gas passage 149 formed between the shield cap exterior housing 139 and metal insert for exit from the torch through an exhaust opening 151 in the shield cap. The shield cap 137, tip 131, gas distributor 135 and electrode 37 are commonly referred to as consumable parts of the torch because the useful life of these parts is typically substantially less than that of the torch itself and, as such, require periodic replacement. Operation of the plasma arc torch of the present invention to perform cutting and welding operations is well known and will not be further described in detail herein.

To assemble the plasma torch of the present invention, such as when the consumable electrode 37 requires replacement, the electrode of the present invention is inserted, upper connecting end 105 first, into the torch head 31 up through the central insulator 39. As the electrode connecting end 105 is pushed upward past the annular seat 115 of the central insulator, the cam surface 121 of the detent 45 on the electrode engages the tapered inner edges 91 of the insulating end caps 75 on the lower ends 67 of the prongs 61. The cam surface 121 of the electrode detent 45 urges the cathode prongs 61 outward to move the cathode detent 43 radially outward to its deflected state against the inward bias of the prongs, thereby increasing the inner diameter D2 of the cathode connecting end 55 at the cathode detent to permit further telescoping movement of the electrode connecting end 105 into the cathode to a position in which the radial detent surface 123 of the electrode detent 45 is above the radial detent surfaces 85 of the cathode detent 43.

Once the electrode detent 45 is pushed upward past the cathode detent 43, the electrode detent comes into radial alignment with the contact surface 89 of the cathode connecting end 55 above the detent surfaces 85 where the inner diameter D1 of the cathode



connecting end is greater than the inner diameter D2 at the cathode detent. The cathode prongs 61, being in their deflected state, create inward biasing forces that urge the prongs to spring or snap inward to move the cathode detent 43 toward its undeflected state. The metal contact surface 89 of the cathode connecting end 55 is urged against the electrode detent 45 to electrically connect the cathode 33 and electrode 37. Inward movement of the cathode detent 43 generally axially aligns (e.g., in generally overlapping or overhanging relationship) the detent surface 123 of the electrode connecting end 105 with the detent surfaces 85 of the cathode connecting end 55. In other words, the electrode radial detent surface 123 is aligned with the cathode radial detent surfaces 85 so that in the event the electrode 37 begins to slide axially outward from the cathode 33 during assembly or disassembly, the electrode radial detent surface 123 engages the radial detent surfaces 85 to inhibit the electrode from falling out of the torch head 31. Since the outer diameter D2 of the electrode connecting end 105 at the electrode detent 43 is greater than the inner diameter of the cathode connecting end 55 at the contact surface 89, the cathode prongs 61 remain in a deflected state after interconnection of the electrode 37 and cathode 33 to maintain the biasing forces urging the prongs inward against the electrode detent 45 for promoting good electrical contact between the cathode and electrode.

To complete the assembly, the gas distributor 135 is placed on the electrode 37, the tip 131 is placed over the electrode to seat on the gas distributor, and the shield cap 137 is placed over the tip and gas distributor and threadably secured to the torch body 35 to axially fix the consumable components in the torch head 31. Upon securing the shield cap 137 to the torch body 35, the shoulder 111 of the gas distributing collar 103 of the electrode 37 engages the annular seat 115 of the central insulator 39 to properly axially position the electrode in the torch head.

To disassemble the torch, the shield cap 137 is removed from the torch body 35 and the tip 131 and gas distributor 135 are slid out of the torch. The electrode 37 is disconnected

from the cathode 37 by pulling axially outward on the lower end 101 of the electrode. The electrode detent surface 123 engages the detent surfaces 85 of the cathode detent 43 and, with sufficient axial pulling force, the electrode detent surface urges the cathode prongs 61 outward to move the cathode detent 43 further toward its deflected state to allow withdrawal of the electrode connecting end 105 from the connecting end 55 of the cathode 33. The rounded detent surface 123 of the annular protrusion 119 facilitates the outward movement of the prongs 61 upon engagement with the detent surfaces 85 of the cathode detent 43.

As illustrated in FIGS. 1-5 and described above, the plasma torch of this first embodiment incorporates an interconnecting cathode 33 and electrode 37 in which the electrode is inserted into the cathode. Alternatively, the electrode 37 may instead be sized and configured for surrounding the cathode 33, with the electrode detent 45 extending radially inward from the electrode connecting end 105 and the cathode detent 43 projecting radially outward from the cathode connecting end 55 such that the cathode prongs 61 are deflected inward upon relative telescoping movement of the cathode and electrode.

FIGS. 6-9 illustrate a second embodiment of a plasma torch of the present invention in which an electrode 237 (as opposed to the cathode 33 of the first embodiment) has a connecting end 305 comprising resilient longitudinally extending prongs 361. As with the first embodiment described above, the torch of this second embodiment includes a cathode, generally indicated at 233, the electrode 237, a central insulator 239, a gas distributor 335, a tip 331 and a shield cap 337. The electrode 237 is configured for coaxial telescoping insertion into the cathode 233 on a longitudinal axis X of the torch for electrical connection with cathode (again referred to broadly as a threadless quick connect/disconnect connection).

In this second embodiment, the central insulator 239 and electrode 237 are formed with radially opposed detents, generally designated 243 and 245, respectively. These detents 243, 245 are interengageable with one another when the electrode 237 is inserted in the torch

head 231 to inhibit axial movement of the electrode relative to the central insulator outward from the torch.

As shown in FIG. 6, the cathode 233 is substantially similar to the cathode 33 of the first embodiment, comprising a head 251, a body 253 and a lower connecting end 255. A central bore 257 extends longitudinally substantially the entire length of the cathode 233 to direct a working gas through the cathode. The connecting end 255 of the cathode 233 is generally of rigid construction and is formed of brass, free of the electrically insulating sleeve 87 and end caps 75 described above in connection with the first embodiment. The diameter of the inner surface of the cathode connecting end 255 is jogged outward to define a shoulder 256 (FIG. 9) for seating a plug 351 in the connecting end. The plug 351 is generally cylindric and has a head 353 sized for seating in the connecting end 255 of the cathode 233 up against the shoulder 256 in frictional engagement with the inner surface of the cathode connecting end to secure the plug in the cathode. A body 355 of the plug 351 extends down from the head and has a substantially smaller diameter than the head so that the outer surface of the body is spaced radially inward from the cathode connecting end 255. The inner surface of the connecting end 255 jogs further outward below the shoulder 256 and head 353 of the plug 351 and defines a contact surface 289 of the cathode connecting end for electrical contact with the electrode. The radial spacing between the contact surface 289 and the plug body 351 defines an annular gap or recess 357 sized for receiving the electrode connecting end 305 therein in electrical contact with the contact surface 289 of the cathode connecting end 255. A lower end 359 of the plug body 351 tapers inward to define a cam surface for urging the electrode connecting end 255 to seat in the recess 357 in electrical contact with the contact surface 289.

The electrode 237 of this second embodiment is generally cylindric and has a solid lower end 301, an upper connecting end 305 adapted for coaxial telescoping insertion in the cathode connecting end 255 and interconnection with the central insulator 239 about the

longitudinal axis X, and a collar 303 intermediate the upper and lower ends of the electrode.

The electrode 237 of the illustrated embodiment is constructed of copper, with an insert (not shown but similar to insert 107 of the first embodiment) of emissive material (e.g., hafnium)

secured in a recess (not shown but similar to recess 109 of the first embodiment) in the

bottom of the electrode in a conventional manner. The collar 303 extends radially outward relative to the upper and lower ends 305, 301 of the electrode 237, thus defining a shoulder

311 between the collar and the upper connecting end of the electrode. A central bore 313

extends longitudinally within the upper connecting end 305 of the electrode 237 generally

from the top of the electrode down into radial alignment with the collar 303 of the electrode.

The top of the electrode 237 is open to provide fluid communication between the cathode central bore 257 and the electrode central bore 313 upon insertion of the electrode 237 in the cathode 233.

Referring to FIGS. 6 and 7, the upper connecting end 305 of the electrode 237

comprises a set of resilient longitudinally extending prongs 361 defined by vertical slots 363

in the electrode connecting end extending generally the length of the central bore 313 of the

electrode. These vertical slots 363 also exhaust working gas from the electrode connecting

end 305 in a manner substantially similar to the openings 117 of the gas distributing collar

103 of the first embodiment described above. The prongs 361 have lower ends 365, integrally

connected to the collar 303 of the electrode 237, and free upper ends 367. The prongs 361 are

sufficiently resilient to permit generally radial movement of the prongs between a normal,

undeflected state and a deflected state in which the prongs are deflected inward toward each

other and the central longitudinal axis X of the torch to decrease the diameter of the electrode

connecting end 305 to enable insertion of the electrode connecting end up into the cathode

connecting end 255, as will be described.

In the preferred embodiment, the electrode detent 245 comprises a radial projection

369 integrally formed with each prong 361 and extending radially outward from the free

upper end 367 of each prong. Thus, it will be seen that the detent 245 is on the connecting end 305 of the electrode 237 for conjoint radial movement with the prongs 361 between an undeflected and deflected state. Each projection 369 is substantially square or rectangular in cross-section (FIG. 9) to define an upper surface 371, a lower radial detent surface 373 and an outer contact surface 375 for electrical contact with the contact surface 289 of the cathode connecting end 255. It is understood, however, that the shape of the detent 245 may vary without departing from the scope of this invention, as long as the detent has a lower radial detent surface 373 extending generally radially outward from the connecting end 305 of the electrode 237 and the electrode is capable of electrical connection with the cathode 239.

Also, in the preferred embodiment the connecting end 305 of the electrode 237 comprises four resilient prongs 361, but this number may vary from one prong to many prongs without departing from the scope of this invention.

The central insulator 239 of this second embodiment includes an annular seat 315 extending radially inward to a diameter substantially less than the outer diameter of the electrode collar 303 such that the shoulder 311 formed by the collar engages the annular seat to limit insertion of the electrode 237 in the cathode 233 and axially position the electrode in the torch head 231. The detent 243 on the central insulator 239 is formed by an annular, radially inward extending protrusion 381 located between the bottom of the cathode 239 and the annular seat 315 of the central insulator. As shown in the illustrated embodiment, the detent 243 is preferably positioned adjacent the bottom of the cathode 233. At the lower end of the protrusion 381, the inner diameter of the central insulator tapers inward to define a cam surface 383 for initiating inward deflection of the electrode prongs 361 to their deflected state upon insertion of the electrode through the central insulator 239. The inner diameter of the central insulator 239 tapers back outward at the upper end of the detent 243 to define a radial detent surface 385 of the central insulator in generally radially and axially opposed relationship with the electrode detent surface 373. The tapered detent surface 385 of the

central insulator detent 243 also provides a cam surface for deflecting the electrode prongs 361 inward to facilitate withdrawal of the electrode 237 from the cathode 233 upon disassembly of the torch. The detent surface 385 of the central insulator 239 preferably tapers outward to a diameter equal to or slightly less than the inner diameter of the contact surface 289 of the cathode connecting end 255 to guide insertion of the electrode connecting end 305 into the cathode connecting end when installing the electrode 237 in the torch.

As seen best in FIG. 9, the electrode detent 245 is sized diametrically larger than the inner diameter of the contact surface 289 of the cathode connecting end 255 so that after insertion of the electrode 237 through the central insulator 239 and into the cathode connecting end, the prongs 261 and detent of the electrode will remain in an inward deflected state. The inward deflected prongs 361 create a biasing force that urges the prongs outward, thereby urging the electrode detent 245 to move radially outward into electrical engagement with the contact surface 289 of the cathode connecting end 255 to electrically connect the electrode 237 and cathode 233.

To assemble the plasma torch of the second embodiment, the electrode 237 is inserted, upper connecting end 305 first, into the torch head up through the central insulator 239. As the electrode connecting end 305 is pushed past the annular seat 315 of the central insulator 239, the upper surfaces 371 of the radial projections 369 on the prongs 361 of the electrode 237 engage the tapered lower cam surface 383 of the central insulator detent 243. The cam surface 383 urges the electrode prongs 361 inward against the outward bias of the prongs to radially move the electrode detent 245 inward to its deflected position, thereby decreasing the outer diameter of the electrode connecting end 305 at the electrode detent to permit further insertion of the electrode connecting end through the central insulator 239 and into the cathode connecting end 255 to a position in which the radial detent surfaces 373 of the electrode detent 245 are above the radial detent surface 385 of the central insulator detent 243.

Once the electrode detent 245 is pushed upward past the central insulator detent 243 and into the cathode connecting end 255, the electrode detent 243 comes into radial alignment with the contact surface 289 of the cathode connecting end 55 where the inner diameter of the cathode connecting end is greater than the inner diameter at the central insulator detent. The electrode prongs 361, being in their deflected state, create outward biasing forces that urge the prongs outward to move the electrode detent 243 toward its undeflected state. The outer contact surfaces 375 of the radial prong projections 369 are urged outward against the contact surface 289 of the cathode connecting end 289 to electrically connect the cathode 233 and electrode 237. Outward movement of the electrode detent 243 generally axially aligns (e.g., in overlapping or overhanging relationship) the detent surfaces 373 of the electrode connecting end 305 with the detent surface 385 of the central insulator 289. In other words, the electrode radial detent surfaces 373 are aligned with the central insulator detent surface 385 so that in the event the electrode 237 begins to slide axially outward from the torch head 231 during assembly or disassembly, the electrode radial detent surfaces 373 engage the radial detent surface 385 of the central insulator 239 to inhibit the electrode from falling out of the torch head 31.

Since the outer diameter of the electrode connecting end 305 at the detent 243 is greater than the inner diameter of the cathode connecting end 255 at the contact surface 289, the electrode prongs 361 remain in an inward deflected state after insertion of the electrode 237 in the cathode 233 to maintain the biasing forces urging the electrode detent 245 outward against the cathode contact surface for promoting good electrical contact between the cathode 233 and electrode. Where slight permanent inward deformation of an electrode prong 361 is present, the outward bias of the prong may not be sufficient to urge the electrode detent 245 into electrical contact with the cathode contact surface 289. In that case, the upper surface 371 of the radial projection 369 on the deformed prong 361 will engage the tapered lower end 359 of the plug body 355 upon insertion of the electrode connecting end 305 into the cathode

connecting end 255. The tapered lower end 359 provides a cam surface that urges the electrode prong 361 outward, thereby moving the electrode detent radially outward to seat in the recess 357 between the plug body 355 and the contact surface 289 with the prong projections 369 in electrical engagement with the contact surface.

5 To complete the assembly, the gas distributor 235 is placed on the electrode 237, the tip 231 is placed over the electrode to seat on the gas distributor, and the shield cap 237 is placed over the tip and gas distributor and threadably secured to the torch body 235 to axially fix the consumable components in the torch head 231. Upon securing the shield cap 237 to the torch body 235, the shoulder 311 of the collar 303 of the electrode 237 engages the  
10 annular seat 315 of the central insulator 239 to properly axially position the electrode in the torch head.

To disassemble the torch, the shield cap 237 is removed from the torch body 235 and the tip 231 and gas distributor 235 are slid out of the torch. The electrode 237 is removed from the torch by pulling axially outward on the lower end 301 of the electrode. The  
15 electrode detent surfaces 373 engage the tapered detent surface 385 of the central insulator detent 243 and, with sufficient axial pulling force, the tapered detent surface urges the electrode prongs 361 further inward to move the electrode detent 245 further toward its deflected state to allow withdrawal of the electrode connecting end 305 from the central insulator 239.

20 As illustrated in this second embodiment, the plasma torch of the present invention incorporates an electrode 237 and central insulator 239 having interengageable detents 245, 243 for inhibiting axial movement of the electrode outward from the torch during assembly of the torch. However, it is understood that instead of the detent 243 extending radially from the central insulator 239, the detent may instead extend radially from the inner surface of the  
25 cathode connecting end 255 in a manner similar to that described above with respect to the first embodiment, without departing from the scope of this invention. Also, the electrode 237



may instead be sized and configured for surrounding the cathode 233, with the electrode  
detent 245 extending radially inward from the electrode connecting end 305 and a  
corresponding detent extending radially outward from the cathode connecting end 255 such  
that the electrode prongs 361 are deflected outward upon relative telescoping movement of  
the cathode and electrode.

Now referring to FIGS. 10a-c, in accordance with the present invention the electrode  
37 of the plasma arc torch of the first embodiment (FIGS. 1-5) has a roughened, or textured  
outer surface 76 along substantially the entire length of the portion of the electrode that  
partially defines (along with the torch tip) the gas passage 133. The textured outer surface 76  
of the electrode 37 may be formed by circular depressions or dimples (indicated as 80 in FIG.  
10a), similar to those formed in the outer cover of a golf ball, or by axially extending grooves  
(indicated as 82 in FIG. 10b) or by one or more spiral, thread-like grooves (indicated as 84 in  
FIG. 10c) in the outer surface of the electrode. The axially extending grooves 82 of the  
electrode 37 of Fig. 10b and the spiral grooves 84 of the electrode 37 of Fig. 10c are sized  
and oriented for turbulating working gas swirling about the outer surface of the electrode in  
the gas passage 133. As an example, the electrode 37 of Fig. 10b has a textured outer surface  
76 formed by about 12-14 axially extending grooves 82 spaced equally about the outer  
surface of the electrode, with each groove having a depth of approximately .015 inches. It  
has been found that forming the textured surface by providing a smaller number of deeper  
grooves 82 is generally preferred over a textured surface formed by providing a greater  
number of shallower grooves since the deeper grooves are more capable of turbulating  
working gas flowing over the outer surface of the electrode.

The spiral grooves 84 of the textured surface 76 of the electrode 37 of Fig. 10c also  
have a depth of about .015 inches. The spiral grooves 84 extend downward within the outer  
surface of the electrode 37 in a direction crosswise, or counter, to the direction that working  
gas swirls about the electrode within the gas passage 133. The pitch of each spiral groove 84

is preferably equal to or less than the pitch of the swirling gas within the gas passage 133 so that the longitudinal component of each groove is at least as great as, or preferably greater than, the longitudinal component of the swirling gas in the gas passage.

The grooves 82, 84 of the electrode 37 of Figs. 10b, 10c may be formed by various methods, such as by knurling, molding or machining the grooves in the outer surface of the electrode. For example, the axially extending grooves 82 of the textured surface 76 of the electrode 37 of the embodiment of Fig. 10b are preferably formed by knurling the outer surface of the electrode. It is understood that the textured outer surface 76 may be formed other than as illustrated in FIGS. 10a-c without departing from the scope of this invention. Also, while the textured electrode 37 of the present invention is shown and described herein as being used in connection with the plasma arc torch of the first embodiment (FIGS. 1-5), it is understood that the textured electrode may be used in other plasma arc torches in which gas is directed through a gas passage 133 in a generally swirling direction, without departing from the scope of this invention.

In accordance with a method of the present invention for improving the useful life of consumable parts of a plasma arc torch, primary working gas is directed to flow downward through the gas passage 133 in a swirling motion about the electrode 37, flowing over the textured outer surface 76 of the electrode. As with any fluid flow in an annular passageway, a hydrodynamic boundary layer (Fig. 13) is established on the outer surface 76 of the electrode 37. As the gas flows over the textured outer surface 76 of the electrode 37, the gas is tumbled or turbulated in the boundary layer (Fig. 14) to increase turbulence in the boundary layer near the outer surface of the electrode, thereby improving the cooling effectiveness of the gas. Providing the textured outer surface 76 of the electrode 37 to promote turbulence of the gas swirling within the gas passage has been found to substantially increase the useful life of an electrode. In particular, it has been found that for a torch in which the working gas flows through the gas passage 133 in a swirling direction (e.g., clockwise from the upper end to the

lower end of the gas passage as illustrated in FIG. 1), the textured outer surface 76 of the electrode 37 is preferably formed to extend within the outer surface of the electrode in a direction other than the direction that working gas swirls about the electrode within the gas passage 133. For example, the axially extending grooves 82 of the electrode 37 of Fig. 10b are oriented generally crosswise to the direction of swirling gas in the gas passage 133. As another example, the spiral grooves 84 of the electrode 37 of Fig. 10c spiral within the outer surface of the electrode in the direction crosswise, or counter (e.g., in a counter-clockwise direction) to the direction of swirling gas within the gas passage 133.

It has also been found that under the conditions that exist inside the gas passage 133, convective cooling of the textured electrode 37 and the tip 131 generally increases with the flow velocity through the annular gas passage between the outer diameter of the electrode and the inner diameter of the tip. The gas flow velocity is generally directly proportional to the volumetric flow rate of the gas through the torch and generally inversely proportional to the dimensions that define the annular space forming the gas passage 133 between the tip 131 and the electrode 37. Thus, to further enhance consumable life (i.e., the useful or working lives of the electrode 37 and tip 131), the beneficial affect derived from the textured surface 76 may be augmented by increasing volumetric flow rates and/or by decreasing the cross-sectional area of the gas passage 133 defined by the electrode and tip. Increasing the volumetric flow rate and/or decreasing the cross-sectional area of the annular gas passage 133 will tend to increase the flow velocity of the gas flowing through the gas passage. The cross-sectional area of the gas passage 133 may be decreased by increasing the outside diameter of the electrode (e.g., by increasing the cross-sectional area of the outer surface of the electrode) and/or by decreasing the inside diameter of the tip (e.g, by decreasing the cross-sectional area of the inner surface of the tip) to narrow the gap between the two parts.

By way of example, the volumetric flow rate for the torch of the present invention is preferably reduced, along with the diameter of the exit orifice 145 of the tip 131, as the

current level at which the torch is operated is reduced. Absent a corresponding decrease in the cross-sectional area of the gas passage 133, the gas flow velocity in the gas passage would be substantially reduced at lower volumetric flow rates, resulting in decreased cooling of the consumable parts. This decrease in cooling can be avoided by using the textured electrode 37 in combination with a higher volumetric flow rate or, more preferably, a reduced size of the cross-sectional area of the gas passage 133 defined by the electrode and tip 131 to provide higher flow velocity in the gas passage for greater cooling, or a combination of both.

However, it has been found that where a non-textured electrode is used, increasing the flow velocity of the gas swirling within the gas passage 133 by decreasing the cross-sectional area of the gas passage provides little or no improvement in the useful life of the non-textured electrode, and may even decrease its useful life.

### Experiment

An experiment was conducted in which a series of tests were performed using the plasma arc torch shown in Figs. 1-5 and described above. For each test, the torch was fitted with an electrode 37 and a tip 131 and operated at a predetermined current level, such as 80 amps or 40 amps, and a predetermined standard volumetric flow rate corresponding to the current level at which the torch was operated, such as 90 standard cubic ft./hr. and 50 standard cubic ft./hr., respectively. As used herein, the standard volumetric flow rate is measured using a conventional gas turbine meter positioned at the exit of the tip 131 at atmospheric pressure and room temperature. In accordance with conventional plasma arc torch design, the central exit orifice 145 of the tip 131 used for operating the torch at 80 amps (e.g., about .055 inches) was greater than the central exit orifice of the tip used for operating the torch at 40 amps (e.g., about .031 inches).

For each test, the outer diameter (e.g., outer surface) of the electrode 37 and the inner diameter (e.g., inner surface) of the tip 131 were sized relative to each other to obtain a

different cross-sectional area of the gas passage 133 formed between the electrode and the tip. In effect, varying the cross-sectional area of the gas passage 133 resulted in variance of a standard flow velocity of working gas swirling within the gas passage 133 about the outer surface of the electrode 37. As used herein, the standard flow velocity is a calculated velocity obtained by dividing the standard volumetric flow rate by the cross-sectional area of the gas passage. The cross-sectional area of the gas passage 133 as used herein is calculated based on the outermost diameter of the electrode 37 and does not reflect any additional spacing between the electrode and the tip 131 resulting from the grooves 82 formed in the outer surface of the electrode.

One set of tests was run at a current level of 80 amps using electrodes 37 having axially extending grooves 82 in their outer surface, with each groove having a depth of about .015 inches. A similar set of tests was run at a current level of 40 amps. For further comparison purposes, a third set of tests was run at a current level of 80 amps using non-textured electrodes and a fourth test was run at a current level of 80 amps using an electrode (not shown) having grooves (not shown) extending substantially circumferentially within its outer surface (e.g., by forming a threaded outer surface having a high pitch, such as about 20 threads/inch to approximate circumferentially oriented grooves).

Each test comprised repeated operation of the torch through a working cycle including starting the torch, piercing a metal workpiece, cutting the workpiece and shutting off the gas flow through the torch. The duration of each working cycle was 11 seconds. Operation of the torch was repeated until a catastrophic failure of the electrode resulted in the torch becoming inoperable without replacement of the electrode. The number of working cycles completed before failure of the electrode was recorded as the useful lifetime of the electrode. The useful lifetime data reported in the table of Fig. 15 is based on conducting each test three times and averaging the resultant useful lifetime data.

According to the results of the experiment, the useful lifetime of the textured electrode 37 incorporated in the torch operated at a current level of 80 amps generally increased with the increased standard flow velocity resulting from decreasing the cross-sectional area of the gas passage 133 between the electrode and the tip 131 while holding constant the current level and the standard volumetric flow rate. While not as pronounced, the useful lifetime of the textured electrode 37 incorporated in the torch operated at 40 amps also generally increased with the increased standard flow velocity resulting from decreasing the cross-sectional area of the gas passage 133 while holding constant the current level and the standard volumetric flow rate.

However, the test results also suggest that when a non-textured electrode is used in the torch, increasing the standard flow velocity of working gas swirling within the gas passage 133 has little or no effect on, or more particularly may actually decrease, the useful lifetime of the electrode where the current level and the standard volumetric flow rate are held constant. Consequently, the resultant advantages obtained by increasing the standard flow velocity of working gas swirling within the gas passage (e.g., by decreasing the cross-sectional area of the gas passage) are achieved in combination with using a textured electrode 37 capable of turbulating the gas flowing over the outer surface of the electrode.

Also, where the electrode having substantially circumferential grooves was incorporated in the torch the useful lifetime of the electrode was substantially less than that of textured electrodes 37 tested at similar standard flow velocities and the same current level and standard volumetric flow rate. Thus, for a plasma arc torch in which the working gas swirls within the gas passage 133 about the electrode 37, the longitudinally extending grooves yield a noticeably greater useful lifetime of the electrode than substantially circumferentially oriented grooves.

Comparing the data obtained for tests in which the torch was operated at a current level of 80 amps with the tests in which the torch was operated at a current level of 40 amps,

it can be seen that the standard flow velocity, and accordingly the useful lifetime of the textured electrode 37, increased for the torch operated at 40 amps by decreasing the cross-sectional area of the gas passage 133 along with the current level and standard volumetric flow rate. Thus, the decrease in standard volumetric flow rate conventionally associated with the decrease in current level is overcome by decreasing the cross-sectional area of the gas passage 133 to maintain a desired standard flow velocity in the gas passage. For example, the cross-sectional area of the gas passage 133 is preferably sized for a given current level at which the torch is operated such that the standard gas flow velocity in the gas passage is at least about 140 ft/sec, more preferably at least about 160 ft/sec, and most preferably at least about 190 ft/sec.

Therefore, in accordance with a further aspect of this invention, a series of electrodes 37 may be provided wherein each electrode corresponds to a different current level and is has a textured surface 76, such as by having grooves 82 (Fig. 10b) extending axially therein, to promote turbulence of working gas flowing over the outer surface of the electrode as the working gas swirls within the gas passage. More particularly, the outer diameter (e.g., outer surface) of the electrode 133 is increased, or stated more broadly, the cross-sectional area of the electrode is increased, as the current level at which the torch is operated decreases. By increasing the cross-sectional area of the electrode 37, the cross-sectional area of the gas passage 133 is correspondingly decreased as the current level decreases to maintain the desired standard flow velocity in the gas passage.

In an alternative embodiment, a series of tips 131 may be provided for a torch having a textured electrode 37 capable of turbulating gas swirling within the gas passage 133 about the outer surface of the electrode. Each of the tips 131 corresponds to a current level at which the torch may be operated. More particularly, the central exit orifice 145 of the tip 131 is decreased as the current level at which the torch operates decreases. The inner diameter (e.g., inner surface) of the tip 131 is decreased, so that the cross-sectional area of the gas passage

133 is correspondingly decreased, as the current level at which the torch is operated decreases to maintain the desired standard flow velocity in the gas passage.

In another embodiment, a series of electrode 37 and tip 131 sets can be provided, with each set including an electrode having a textured outer surface 76 and one tip. Each set corresponds to a particular current level at which the torch may be operated. The central exit orifice 145 of the tip 131 is decreased as the current level at which the torch operates decreases. The electrode 37 outer diameter and tip 131 inner diameter are sized relative to each other such that the cross-sectional area of the gas passage 133 is correspondingly decreased as the current level at which the torch is operated decreases to generally maintain the desired standard flow velocity in the gas passage.

Thus, these sets are designed so that the dimensions of the gas passage 133 for each set decreases as the current level (amperage) decreases. Thus, if the standard volumetric flow rate is decreased at lower current levels, the decreased dimensions of the gas flow passage 133 will result in a higher standard flow velocity within the gas passage for good cooling even at the lower standard volumetric flow rates. The cross-sectional area of the annular gas passage 133 of each set can be varied by changing the dimensions of either or both the electrode 37 and tip 131 to correspond to the desired standard flow velocity through the gas passage for increasing the useful lifetime of the electrode.

FIG. 11 illustrates the torch head 31 of the plasma arc torch of FIG. 1 with an outer surface 90 of the torch tip 131 being roughened or otherwise textured in accordance with the present invention. In this embodiment, convective cooling of the torch tip 131 is accomplished by directing a flow of non-swirling gas through the secondary gas passage 149 over the textured outer surface 90 of the tip. It is understood, however, that the gas in the secondary gas passage may instead have a swirling motion without departing from the scope of this invention. The textured outer surface 90 of the tip 131 may be formed by generally concentric grooves 92 in the outer surface of the tip and spaced at intervals along the surface



or by one or more spiral grooves (not shown), oriented either clockwise or counterclockwise, in the tip outer surface so that the grooves are in a generally crosswise orientation relative to the gas flowing through the secondary gas passage 149.

FIG. 11a illustrates the torch head 31 of FIG. 11 with an inner surface 94 of the torch tip 131 being roughened or otherwise textured in accordance with the present invention. In this embodiment, convective cooling of the torch tip 131 is accomplished by directing gas to flow down through the gas passage 133 in a generally swirling direction over the textured inner surface 94 of the tip. The textured inner surface 94 of the tip 131 may be formed by axially extending grooves 96 in the inner surface of the tip, or by dimples (not shown but similar to the dimples 80 of the electrode 37 of Fig. 10a) or one or more spiral grooves (not shown but similar to the grooves 84 in the electrode 37 of Fig. 10c). In this manner the axially extending grooves 96 or spiral grooves are oriented generally crosswise relative to the direction that gas swirls about the electrode within the gas passage 133 over the inner surface of the tip.

FIG. 12 illustrates another embodiment of a torch head 431 of a plasma arc torch of the present invention. This torch is of a dual-gas type in which a secondary working gas, separate from the primary working gas, is utilized during operation of the torch. In this torch, primary working gas enters the torch at an inlet 494 and is directed into and through the gas passage 433 formed by the electrode 437 and tip 531 before being exhausted from the torch through the central exit orifice 566 of the tip. The torch head 431 includes a shield cap assembly 596 comprising a shield cap 539 generally surrounding the torch tip 531 in spaced relationship therewith to partially define a secondary gas passage 549. The assembly 596 also includes a retainer 598 for use in securing the shield cap assembly to the torch body 600. Secondary working gas is received in the torch head 431 via a second inlet 602 and is directed through the torch to the secondary gas passage 549 for exhaust from the torch via a central exhaust opening 551 of the shield cap 539.

As shown in FIG. 12, an inner surface 604 of the shield cap 539 is roughened or otherwise textured in accordance with the present invention. Convective cooling of the shield cap 539 of the illustrated embodiment is accomplished by directing non-swirling secondary working gas through the secondary gas passage 549 in a generally axial direction over the inner surface 604 of the shield cap 539. However, it is understood that secondary gas may flow through the secondary gas passage in a generally swirling motion without departing from the scope of the invention. The textured inner surface 604 of the shield cap 539 may be formed by concentric grooves 606 in the inner surface of the cap and spaced at intervals along the inner surface or by one or more spiral grooves (not shown), oriented either clockwise or counterclockwise, such that the grooves have a generally crosswise orientation relative to the flow of secondary working gas through the secondary gas passage 549.

While the textured surfaces of the consumable parts of the torch are generally shown and described above as being formed by cutting into the surface of the consumable part, it is understood that the textured surface may be formed by raising the surface of the part, such as by forming bumps, fins or other suitable formations on the surface of the part, without departing from the scope of this invention.

The embodiments illustrated and described above can be used in combination with each other to enhance the useful life of all of the consumable parts of the plasma arc torch. For example, it is contemplated that texturing the opposing surfaces that form an annular gas passage 133 (e.g., the outer surface of the electrode 37 and the inner surface of the tip 131, or the outer surface of the tip and the inner surface of the shield cap 549) will create additional turbulence in the hydrodynamic boundary layer of the cooling gas to further improve convective cooling of each consumable part.

In view of the above, it will be seen that the several objects of the invention are achieved and other advantageous results attained.

As various changes could be made in the above constructions without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 1041 1042 1043 1044 1045 1046 1047 1048 1049 1050 1051 1052 1053 1054 1055 1056 1057 1058 1059 1060 1061 1062 1063 1064 1065 1066 1067 1068 1069 1070 1071 1072 1073 1074 1075 1076 1077 1078 1079 1080 1081 1082 1083 1084 1085 1086 1087 1088 1089 1090 1091 1092 1093 1094 1095 1096 1097 1098 1099 1100 1101 1102 1103 1104 1105 1106 1107 1108 1109 1110 1111 1112 1113 1114 1115 1116 1117 1118 1119 1120 1121 1122 1123 1124 1125 1126 1127 1128 1129 1130 1131 1132 1133 1134 1135 1136 1137 1138 1139 1140 1141 1142 1143 1144 1145 1146 1147 1148 1149 1150 1151 1152 1153 1154 1155 1156 1157 1158 1159 1160 1161 1162 1163 1164 1165 1166 1167 1168 1169 1170 1171 1172 1173 1174 1175 1176 1177 1178 1179 1180 1181 1182 1183 1184 1185 1186 1187 1188 1189 1190 1191 1192 1193 1194 1195 1196 1197 1198 1199 1200 1201 1202 1203 1204 1205 1206 1207 1208 1209 1210 1211 1212 1213 1214 1215 1216 1217 1218 1219 1220 1221 1222 1223 1224 1225 1226 1227 1228 1229 1230 1231 1232 1233 1234 1235 1236 1237 1238 1239 1240 1241 1242 1243 1244 1245 1246 1247 1248 1249 1250 1251 1252 1253 1254 1255 1256 1257 1258 1259 1260 1261 1262 1263 1264 1265 1266 1267 1268 1269 1270 1271 1272 1273 1274 1275 1276 1277 1278 1279 1280 1281 1282 1283 1284 1285 1286 1287 1288 1289 1290 1291 1292 1293 1294 1295 1296 1297 1298 1299 1300 1301 1302 1303 1304 1305 1306 1307 1308 1309 1310 1311 1312 1313 1314 1315 1316 1317 1318 1319 1320 1321 1322 1323 1324 1325 1326 1327 1328 1329 1330 1331 1332 1333 1334 1335 1336 1337 1338 1339 1340 1341 1342 1343 1344 1345 1346 1347 1348 1349 1350 1351 1352 1353 1354 1355 1356 1357 1358 1359 1360 1361 1362 1363 1364 1365 1366 1367 1368 1369 1370 1371 1372 1373 1374 1375 1376 1377 1378 1379 1380 1381 1382 1383 1384 1385 1386 1387 1388 1389 1390 1391 1392 1393 1394 1395 1396 1397 1398 1399 1400 1401 1402 1403 1404 1405 1406 1407 1408 1409 1410 1411 1412 1413 1414 1415 1416 1417 1418 1419 1420 1421 1422 1423 1424 1425 1426 1427 1428 1429 1430 1431 1432 1433 1434 1435 1436 1437 1438 1439 1440 1441 1442 1443 1444 1445 1446 1447 1448 1449 1450 1451 1452 1453 1454 1455 1456 1457 1458 1459 1460 1461 1462 1463 1464 1465 1466 1467 1468 1469 1470 1471 1472 1473 1474 1475 1476 1477 1478 1479 1480 1481 1482 1483 1484 1485 1486 1487 1488 1489 1490 1491 1492 1493 1494 1495 1496 1497 1498 1499 1500 1501 1502 1503 1504 1505 1506 1507 1508 1509 1510 1511 1512 1513 1514 1515 1516 1517 1518 1519 1520 1521 1522 1523 1524 1525 1526 1527 1528 1529 1530 1531 1532 1533 1534 1535 1536 1537 1538 1539 1540 1541 1542 1543 1544 1545 1546 1547 1548 1549 1550 1551 1552 1553 1554 1555 1556 1557 1558 1559 1560 1561 1562 1563 1564 1565 1566 1567 1568 1569 1570 1571 1572 1573 1574 1575 1576 1577 1578 1579 1580 1581 1582 1583 1584 1585 1586 1587 1588 1589 1590 1591 1592 1593 1594 1595 1596 1597 1598 1599 1600 1601 1602 1603 1604 1605 1606 1607 1608 1609 1610 1611 1612 1613 1614 1615 1616 1617 1618 1619 1620 1621 1622 1623 1624 1625 1626 1627 1628 1629 1630 1631 1632 1633 1634 1635 1636 1637 1638 1639 1640 1641 1642 1643 1644 1645 1646 1647 1648 1649 1650 1651 1652 1653 1654 1655 1656 1657 1658 1659 1660 1661 1662 1663 1664 1665 1666 1667 1668 1669 1670 1671 1672 1673 1674 1675 1676 1677 1678 1679 1680 1681 1682 1683 1684 1685 1686 1687 1688 1689 1690 1691 1692 1693 1694 1695 1696 1697 1698 1699 1700 1701 1702 1703 1704 1705 1706 1707 1708 1709 1710 1711 1712 1713 1714 1715 1716 1717 1718 1719 1720 1721 1722 1723 1724 1725 1726 1727 1728 1729 1730 1731 1732 1733 1734 1735 1736 1737 1738 1739 1740 1741 1742 1743 1744 1745 1746 1747 1748 1749 1750 1751 1752 1753 1754 1755 1756 1757 1758 1759 1760 1761 1762 1763 1764 1765 1766 1767 1768 1769 1770 1771 1772 1773 1774 1775 1776 1777 1778 1779 1780 1781 1782 1783 1784 1785 1786 1787 1788 1789 1790 1791 1792 1793 1794 1795 1796 1797 1798 1799 1800 1801 1802 1803 1804 1805 1806 1807 1808 1809 1810 1811 1812 1813 1814 1815 1816 1817 1818 1819 1820 1821 1822 1823 1824 1825 1826 1827 1828 1829 1830 1831 1832 1833 1834 1835 1836 1837 1838 1839 1840 1841 1842 1843 1844 1845 1846 1847 1848 1849 1850 1851 1852 1853 1854 1855 1856 1857 1858 1859 1860 1861 1862 1863 1864 1865 1866 1867 1868 1869 1870 1871 1872 1873 1874 1875 1876 1877 1878 1879 1880 1881 1882 1883 1884 1885 1886 1887 1888 1889 1890 1891 1892 1893 1894 1895 1896 1897 1898 1899 1900 1901 1902 1903 1904 1905 1906 1907 1908 1909 1910 1911 1912 1913 1914 1915 1916 1917 1918 1919 1920 1921 1922 1923 1924 1925 1926 1927 1928 1929 1930 1931 1932 1933 1934 1935 1936 1937 1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071 2072 2073 2074 2075 2076 2077 2078 2079 2080 2081 2082 2083 2084 2085 2086 2087 2088 2089 2090 2091 2092 2093 2094 2095 2096 2097 2098 2099 2100 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114 2115 2116 2117 2118 2119 2120 2121 2122 2123 2124 2125 2126 2127 2128 2129 2130 2131 2132 2133 2134 2135 2136 2137 2138 2139 2140 2141 2142 2143 2144 2145 2146 2147 2148 2149 2150 2151 2152 2153 2154 2155 2156 2157 2158 2159 2160 2161 2162 2163 2164 2165 2166 2167 2168 2169 2170 2171 2172 2173 2174 2175 2176 2177 2178 2179 2180 2181 2182 2183 2184 2185 2186 2187 2188 2189 2190 2191 2192 2193 2194 2195 2196 2197 2198 2199 2200 2201 2202 2203 2204 2205 2206 2207 2208 2209 2210 2211 2212 2213 2214 2215 2216 2217 2218 2219 2220 2221 2222 2223 2224 2225 2226 2227 2228 2229 2230 2231 2232 2233 2234 2235 2236 2237 2238 2239 2240 2241 2242 2243 2244 2245 2246 2247 2248 2249 2250 2251 2252 2253 2254 2255 2256 2257 2258 2259 2260 2261 2262 2263 2264 2265 2266 2267 2268 2269 2270 2271 2272 2273 2274 2275 2276 2277 2278 2279 2280 2281 2282 2283 2284 2285 2286 2287 2288 2289 2290 2291 2292 2293 2294 2295 2296 2297 2298 2299 2300 2301 2302 2303 2304 2305 2306 2307 2308 2309 2310 2311 2312 2313 2314 2315 2316 2317 2318 2319 2320 2321 2322 2323 2324 2325 2326 2327 2328 2329 2330 2331 2332 2333 2334 2335 2336 2337 2338 2339 2340 2341 2342 2343 2344 2345 2346 2347 2348 2349 2350 2351 2352 2353 2354 2355 2356 2357 2358 2359 2360 2361 2362 2363 2364 2365 2366 2367 2368 2369 2370 2371 2372 2373 2374 2375 2376 2377 2378 2379 2380 2381 2382 2383 2384 2385 2386 2387 2388 2389 2390 2391 2392 2393 2394 2395 2396 2397 2398 2399 2400 2401 2402 2403 2404 2405 2406 2407 2408 2409 2410 2411 2412 2413 2414 2415 2416 2417 2418 2419 2420 2421 2422 2423 2424 2425 2426 2427 2428 2429 2430 2431 2432 2433 2434 2435 2436 2437 2438 2439 2440 2441 2442 2443 2444 2445 2446 2447 2448 2449 2450 2451 2452 2453 2454 2455 2456 2457 2458 2459 2460 2461 2462 2463 2464 2465 2466 2467 2468 2469 2470 2471 2472 2473 2474 2475 2476 2477 2478 2479 2480 2481 2482 2483 2484 2485 2486 2487 2488 2489 2490 2491 2492 2493 2494 2495 2496 2497 2498 2499 2500 2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516 2517 2518 2519 2520 2521 2522 2523 2524 2525 2526 2527 2528 2529 2530 2531 2532 2533 2534 2535 2536 2537 2538 2539 2540 2541 2542 2543 2544 2545 2546 2547 2548 2549 2550 2551 2552 2553 2554 2555 2556 2557 2558 2559 2560 2561 2562 2563 2564 2565 2566 2567 2568 2569 2570 2571 2572 2573 2574 2575 2576 2577 2578 2579 2580 2581 2582 2583 2584 2585 2586 2587 2588 2589 2590 2591 2592 2593 2594 2595 2596 2597 2598 2599 2600 2601 2602 2603 2604 2605 2606 2607 2608 2609 2610 2611 2612 2613 2614 2615 2616 2617 2618 2619 2620 2621 2622 2623 2624 2625 2626 2627 2628 2629 2630 2631 2632 2633 2634 2635 2636 2637 2638 2639 2640 2641 2642 2643 2644 2645 2646 2647 2648 2649 2650 2651 2652 2653 2654 2655 2656 2657 2658 2659 2660 2661 2662 2663 2664 2665 2666 2667 2668 2669 2670 2671 2672 2673 2674 2675 2676 2677 2678 2679 2680 2681 2682 2683 2684 2685 2686 2687 2688 2689 2690 2691 2692 2693 2694 2695 2696 2697 2698 2699 2700 2701 2702 2703 2704 2705 2706 2707 2708 2709 2710 2711 2712 2713 2714 2715 2716 2717 2718 271